Investigating Benefits and Challenges of Converting Coal Power Plants to Nuclear Power Plants

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Outline

1. **Introduction and Overview**
   - Research Team
   - External Reviewers
2. **Components of the Study**
   - Siting Evaluation
   - Techno-Economic Analysis
   - Regional Economic and Environmental Impact Analysis
3. **Summary and Conclusions**

Research Questions

- Are there reactor siting opportunities at retired and operating coal plant sites?
- What are the main decision drivers making C2N projects attractive?
- What are the socioeconomic impacts from a C2N transition?

SA&I Analysis on C2N in Context

FASTEST PATH TO ZERO
UNIVERSITY OF MICHIGAN

Microsoft

Bryden Wood

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

MIT

TERRA PRAXIS

University at Buffalo

NEI

GAIN Gateway for Accelerated Innovation in Nuclear

TerraPower
A Nuclear Innovation Company

TVA

Southern Company

scottmadden
MANAGEMENT CONSULTANTS

CATF
CLEAN AIR TASK FORCE

SODI
SOUTHERN OHIO DIVERSIFICATION INITIATIVE

EPRI ELECTRIC POWER RESEARCH INSTITUTE

NRIC National Reactor Innovation Center

orano
Giving nuclear energy its full value
Orano Federal Services, LLC

INL
Idaho National Laboratory

Siting Evaluation

1. Are there reactor siting opportunities at retired coal plant sites?
2. Select a candidate site for economic analyses.
3. Stretch Goal: What are the siting opportunities at operating coal plant sites?

1 – Overview

- **Reactor siting opportunities at retired coal power plant (CPP) sites**
  - What is the scope? (i.e., how many sites should be considered?)
  - Insight on capacity availability at utility and independent power producer (IPP) sites
- **Selection of an arbitrary CPP site for economic C2N backfit analysis**
  - Team opted to focus on a Midwest site for the case study
    - Ensure that selected site would be generic and apolitical
    - Avoid regions where C2N is being actively considered
  - Developed a composite CPP site, based on
    - A retired generator rated at about 600 MWe (retired in last 10 years)
    - An operating generator rated at about 600 MWe (planned to retire in next 10 years)
    - Either generator can be replaced by a small reactor technology; both can be replaced by a large reactor technology
- **Reactor siting opportunities at operating CPP sites**
  - What is the scope?
  - Insight on capacity availability
- **Data source is DOE Energy Information Administration data through August 2021**
  - Latest available data at the initiation of the study
  - Use Oak Ridge Siting Analysis tool for Power Generation Expansion (OR-SAGE) process for evaluation

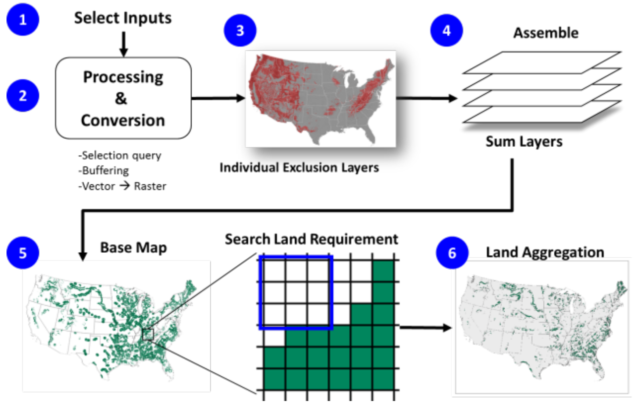
2 – Approach

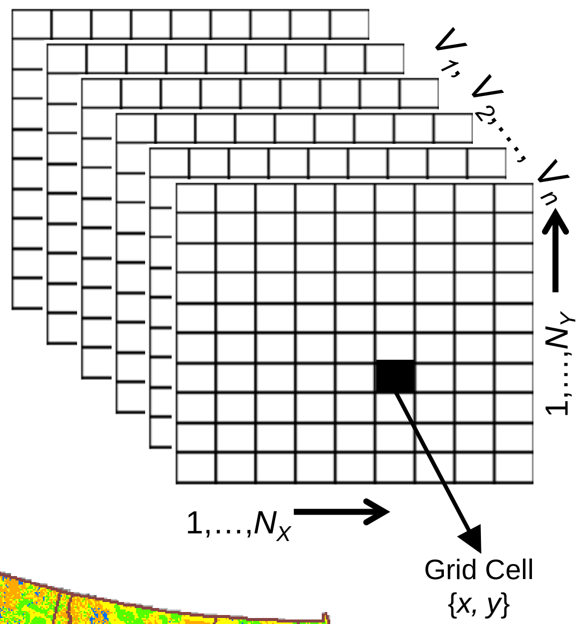
- **EIA data indicated 814 retired generators at 349 CPP sites**
  - Removed all sites retired prior to 2012 (assumed infrastructure is now gone)
  - Removed all sites that were not utility or IPP sites (because likely not first movers)
  - Used OR-SAGE to evaluate small central area of remaining plants
  - Provided 336 generators at 157 CPP sites for further evaluation
  - Binned sites by region
- **Subsequently applied OR-SAGE to larger area around each retired plant**
  - Area around the site center points within a 0.5- and 1-mile radii (~500 acres and 2,000 acres) evaluated using OR-SAGE siting parameters
    - Evaluated siting for small modular reactors and small advanced non-light-water reactors (ARs)
      - Similar siting parameters
    - Evaluated siting for large light-water reactors (may be advanced, but also large)
- **Applied similar area evaluation to operating CPP sites**
  - EIA indicated 581 operating generators at 273 sites
  - Removed all sites that were not utility or IPP sites (i.e., not first movers)
  - Provided 497 generators at 237 CPP sites for further evaluation

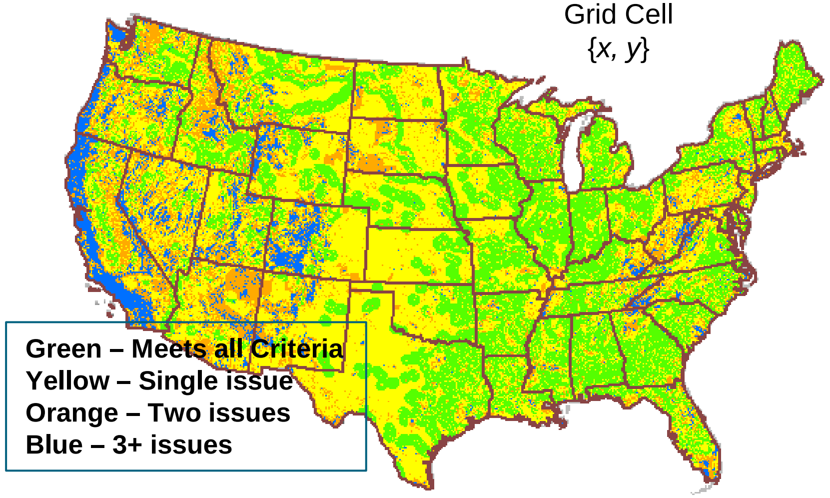
2 – Approach: OR-SAGE Method

Objectives:
- Use industry-accepted parameters for screening
- Use array of Geographic Information System (GIS) data sources and spatial modeling capabilities at ORNL

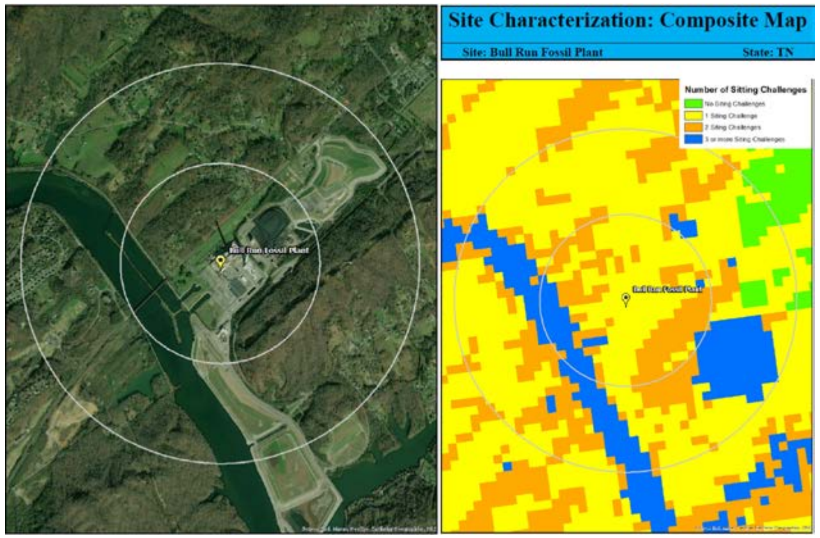
Approach:
- Adapted 2002 EPRI Siting Guide screening criteria, NRC RG 4.7, and approach for obtaining early site permits (ESPs) for nuclear power plants to GIS technology
- Use ~ 50 datasets to scan the contiguous U.S. (~1.8 billion acres) using 100 m by 100 m grid cells (2.5 acres) – Results in visual database







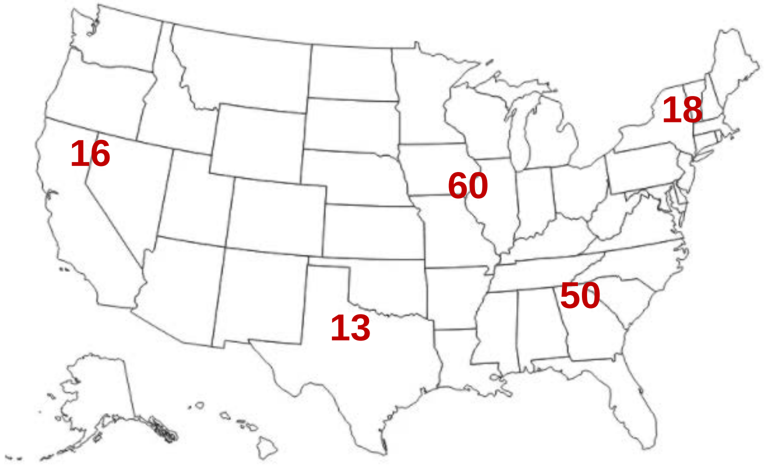
Study applied OR-SAGE evaluation to specific sites as shown below. Concentric circles indicate 0.5- and 1-mile radii (~500 acres and 2,000 acres) around EIA data center point.



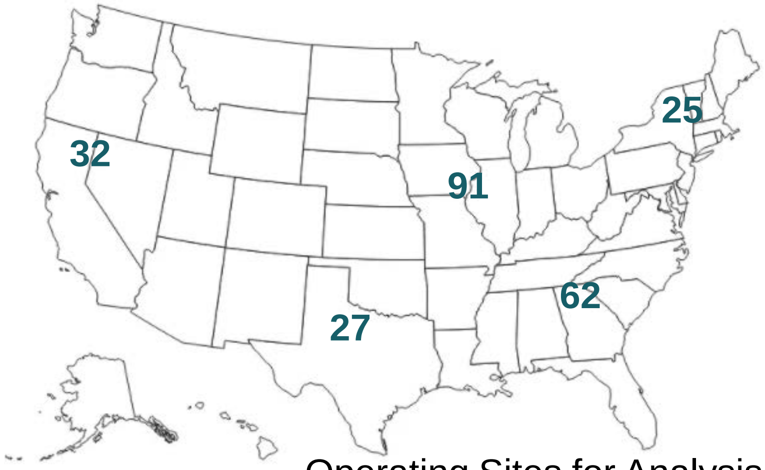
Visual evaluation was not practical for the hundreds of recently retired and operational CPP sites to be evaluated in this study. Therefore, as discussed in the report, a numerical spreadsheet evaluation of the cells surrounding each site was conducted.

2 – Approach: Parameters Evaluated

- **Population Density**
  - Within 4 miles of population centers for ARs
  - Within 20 miles of population centers for large LWRs
- **Safe Shutdown Earthquake**
- **Faults**
- **Protected Land**
- **Slope**
- **Landslide**
- **Wetlands and Open Water**
- **Floodplain**
- **Hazardous Facilities**
- **Availability of Make-up Cooling Water**
  - Large LWRs only



Retired Sites for Analysis



Operating Sites for Analysis

3 – Technical Results

- **Recently retired CPP sites evaluated with OR-SAGE using the logic presented in the approach**
  - 80% are amenable to SMR and AR siting
  - SMR and AR capacity potential of 64.8 GWe to be backfit at 125 sites
  - 22% are amenable to large LWR siting

Recently Retired CPPs	Sites	Amenable @ 0.5-miles	CPP retired in last 6 years	Dedicated cooling source
AR Total	157	125	67	37
LWR Total	157	35	21	15

- **Operating CPP sites evaluated with OR-SAGE using the logic presented in the approach**
  - 80% are amenable to SMR and AR siting
  - SMR and AR capacity potential of 198.5 GWe to be backfit at 190 sites
  - 40% are amenable to large LWR siting

Operating CPPs	Sites	Amenable @ 0.5-miles	Dedicated cooling source
AR Total	237	190	131
LWR Total	237	96	65

4 – Summary

- **Review of currently retired coal-fired assets indicates that the economical advantage that may exist for the C2N backfit at these facilities tends to degrade quickly**
  - Demolition, land sale, land reuse, etc.
  - Potential for backfit of advanced nuclear technologies at CPP sites would appear to strongly favor currently operating units.
- **32% of operating utility and IPP generators have a scheduled retirement date reported to EIA**
  - Timelines to backfit nuclear need to be considered
  - Nuclear replacement generation options need to be incorporated into utility integrated resource plans
  - More work with non-nuclear utilities and IPPs may be insightful to all parties
- **Significant siting opportunities appear to exist for C2N backfit at CPPs**
  - OR-SAGE attempts to replicate 10 CFR 100 siting requirements through application of relevant NRC and EPRI siting guidance
  - 38 states had at least 1 amenable site based on this high-level analysis
  - Decarbonization opportunity and proactive climate change discussion
  - Job transition

Techno-Economic Analysis

What are the main decision drivers making C2N projects attractive?

1 – Overview

- **What are the main decision drivers making C2N projects attractive?**
    - **Compatibility Analysis**: considered different types of C2N projects and discussed compatibility based on different CPP and NPP technologies
        - *Technical compatibility analysis based on subject matter expertise*
    - **Project Model**: built cost and timeline model for different C2N projects identified, showing range of savings between 15-35% in OCC when compared with greenfield projects
        - *Model based on cost data from EEDB and subject matter expertise*
    - **Decision Drivers**: used a novel agent-based modeling approach of Midwest electricity market, showed preference of agents in deploying C2N project over greenfield
        - *Still preliminary results and will need to include risks and additional sensitivity analyses*

2 – Approach

- **<u>Compatibility Analysis</u>: Which NPP technologies could be technically suitable to repower different CPP technologies?**
  - Characterized different types of C2N projects
  - Developed mapping of possible C2N project types and NPP technologies for different site reuse scenarios

- **<u>Project Model</u>: For different C2N projects, which components can be re-used, and what are the associated project costs and timeline?**
  - Reviewed components in common between NPP and CPP based on EEDB data, and estimated potential OCC savings
  - Assessed project timeline and other cost estimates based on literature and subject matter expertise

- **<u>Decision Drivers</u>: What decision drivers influence the deployment viability of different C2N projects?**
  - Developed Midwest-based electricity market model using A-LEAF
  - Used agent-based capacity expansion approach to model agent's decisions to repower their retiring CPPs with different types of C2N projects

3 – Technical Results: Compatibility Analysis

- **Which NPP technologies could be technically suitable to repower different CPP technologies?**
  - Characterized different types of C2N projects, as opposed to pure greenfield NPP project:
    - C2N#0: CPP retired and new NPP built on separate site
    - C2N#1: NPP reuses site, electrical and heat-sink components only
    - C2N#2: same as #1 PLUS **direct** reuse of steam-cycle components
    - C2N#3: same as #1 PLUS **indirect** reuse of steam-cycle components (using intermediary thermal energy storage)

3 – Technical Results: Compatibility Analysis

- **Which NPP technologies could be technically suitable to repower different CPP technologies?**
  - Developed mapping of C2N project types available for different CPP/NPP technologies
    - Electric and thermal power level and waste heat removal capacity – electrical and heat sink components
    - Technology compatibility (operating temperature/pressure in the steam cycle) – balance of plant components

Scenario description	CPP	NPP	Proposed C2N types (in addition to C2N#0 and C2N#1)
1 NPP replaces 1 CPP unit (similar size in terms of electrical power capacity and waste heat removal)	Any type	PWR	C2N#1
	Sub-Critical	SFR	C2N#2
	Super-Critical or Ultra Super-Critical	SFR	C2N#1
	Any type	VHTR	C2N#2
	Sub-Critical	SFR+TES	C2N#3

3 – Technical Results: Project Model

- **For different C2N projects, which components can be re-used and what are the associated project costs and timeline?**
  - Reviewed components in common between NPP and CPP based on EEDB data, and estimated potential OCC savings

Example of nuclear technologies (representatives of C2N project)	PWR (C2N#1)	VHTR (C2N#2)	SFR (C2N#3)	*Min/Max savings in C2N projects*	
Components of OCC (greenfield construction)					
Initial fuels inventory	7%	6%	11%	*0%*	*0%*
Other costs (transmission, owner's, etc.)	10%	10%	10%	*100%*	*100%*
Land and land rights	0.3%	0.3%	0.2%	*100%*	*100%*
Structure and improvements	15%	10%	12%	*0%*	*24%*
Reactor plant equipment	18%	30%	29%	*0%*	*1%*
Turbine plant equipment	15%	14%	10%	*0%*	*99%*
Electric plant equipment	5%	5%	4%	*42%*	*78%*
Miscellaneous plant equipment	2%	1%	1%	*6%*	*91%*
Main condenser and heat rejection system	3%	2%	2%	*0%*	*100%*
Total indirect costs	25%	21%	21%	*16%*	*39%*

3 – Technical Results: Project Model

- **For different C2N projects, which components can be re-used and what are the associated project costs and timeline?**
  - Assessed cost estimates based on literature and subject matter expertise, accounting for OCC (including D&D for the CPP) and O&M.
  - *Developed a conservative case to provide range – cost to refurbish any re-used CPP components is currently not accounted for, due to lack of data*

Project type	Example Reactor Type	Total Project OCC
		$/kW
Greenfield	PWR	$4,572
C2N#0	PWR	$4,799
C2N#1	PWR	$3,598
C2N#2	HTGR	$3,951
C2N#3	SFR	$3,398

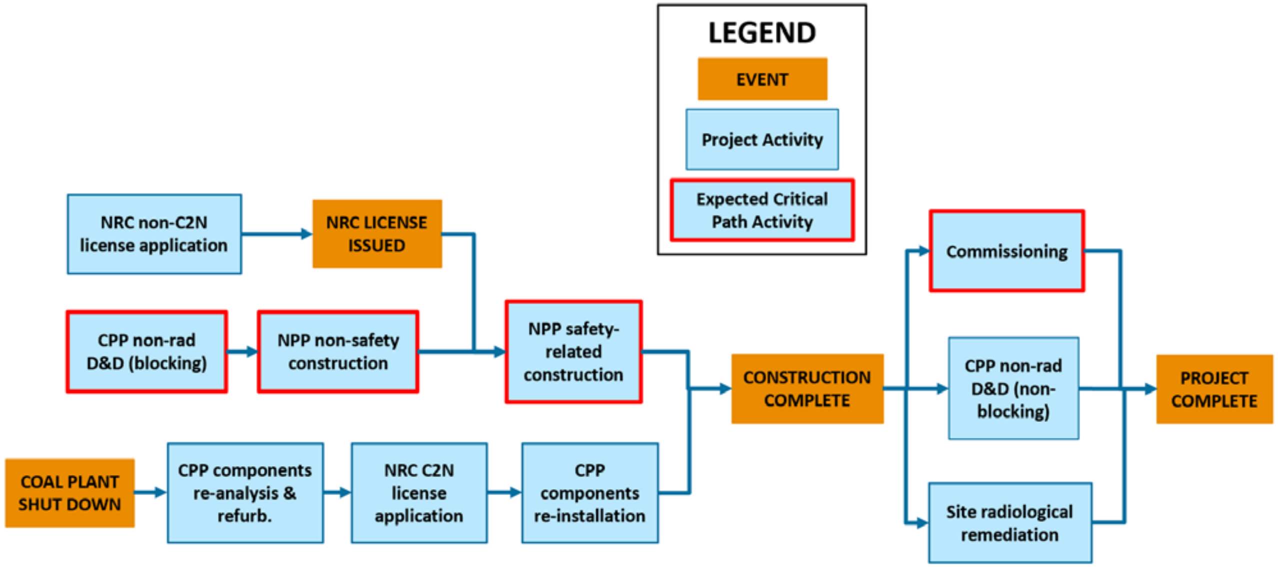
- C2N project can reduce project OCC when compared with equivalent **greenfield**:
  - C2N#1: 15-25%
  - C2N#2 and #3: 17-35%
- Added cost of D&D for the CPP is estimated at 2-4% of the OCC
- *Decommissioning cost of CPP may be more significant in terms of risks. This needs further consideration.*

3 – Technical Results: Project Model

- **For different C2N projects, which components can be re-used and what are the associated project costs and timeline?**
  - Assessed project timeline and other cost estimates based on literature and subject matter expertise
    - Developed simplified "project plan" for each C2N project, with associated timeline
    - Estimated project duration with spending and revenue distribution
    - Some projects types (C2N#0 and #3) display more attractive revenue distribution

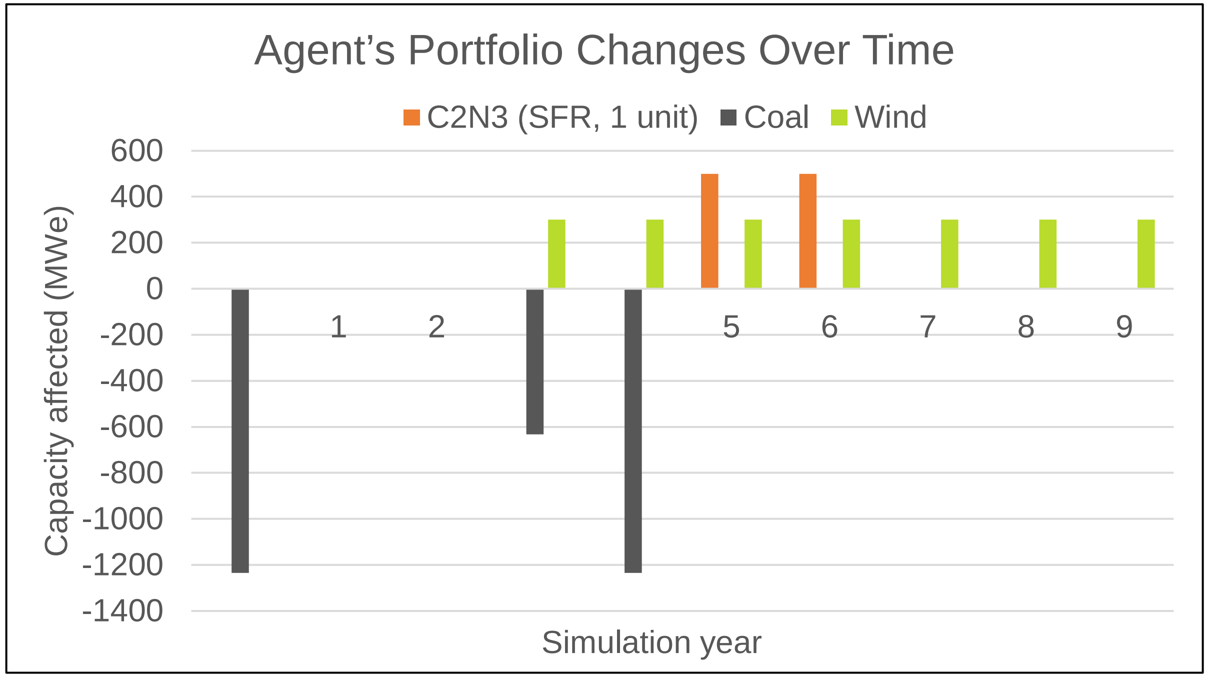
Project type	Example Reactor Type	Total OCC	Required revenue gap
		$/kW	years
Greenfield	PWR	$4,572	0
C2N#0	PWR	$4,799	0
C2N#1	PWR	$3,598	6.75
C2N#2	HTGR	$3,951	6.5
C2N#3	SFR	$3,398	2.75

Project plan example for C2N#3



3 – Technical Results: Decision Drivers

- **What decision drivers influence the deployment viability of different C2N projects?**
  - Developed an electricity market model using publicly available data
  - Use agent-based capacity expansion approach to model generation-owner agents’ decisions to repower their retiring CPPs with different types of C2N projects



- Simulation results:
  - Capacity changes made over time by a large, relatively liquid, diversified portfolio operator are shown on the left
  - This agent repowers two coal units with C2N#3 type projects
  - C2N#3 is preferred due to low capital costs and short revenue gaps, despite its higher operating costs than C2N#1

4 – Summary

- **This analysis provides preliminary confirmation that C2N projects could offer tangible economic value to utility firms.**
- **C2N projects can be categorized by the extent of site infrastructure and equipment to be reused. Different NPPs are most compatible with each of the three project types.**
- **Each category of C2N project is associated with different levels of benefits and drawbacks, which were quantified in this study.**
  - C2N#1 to #3 projects had estimated savings between 15-35% in OCC when compared with greenfield projects.
  - Different C2N projects show more beneficial revenue profiles with reduced/eliminated revenue gap between closure of CPP and startup of NPP.
- **Preliminary assessment of decision drivers was completed using novel agent-based capacity expansion approach. This showed preference of agents for C2N projects over greenfield (due to benefits highlighted above).**

Economic and Environmental Impacts

What are the socioeconomic impacts from a C2N transition?

1-Overview

- **Annual economic impact on composite, analysis region, net change from "All-Coal" to "All-Nuclear" scenario**
  - New economic activity: Up to $275 million
  - New Jobs: 650
  - New income: $102 million
- **Tax impact from CPP closure**
  - In representative county CPP accounts for almost 1/3 of tax revenue
- **Environmental Impacts (IMPLAN / EPA)**
  - PP greenhouse gases reduced by 99%
  - Coal mining and long-term waste storage not included in this study
- **Statewide workforce transition from C2N**
  - 797 net jobs retained or created by PP, supply chain, and community
- **3-Part approach: Economic Impacts, Environmental Impacts, Workforce Transition**

2-Approach: IMPLAN Input-Output Model Overview & Methodology

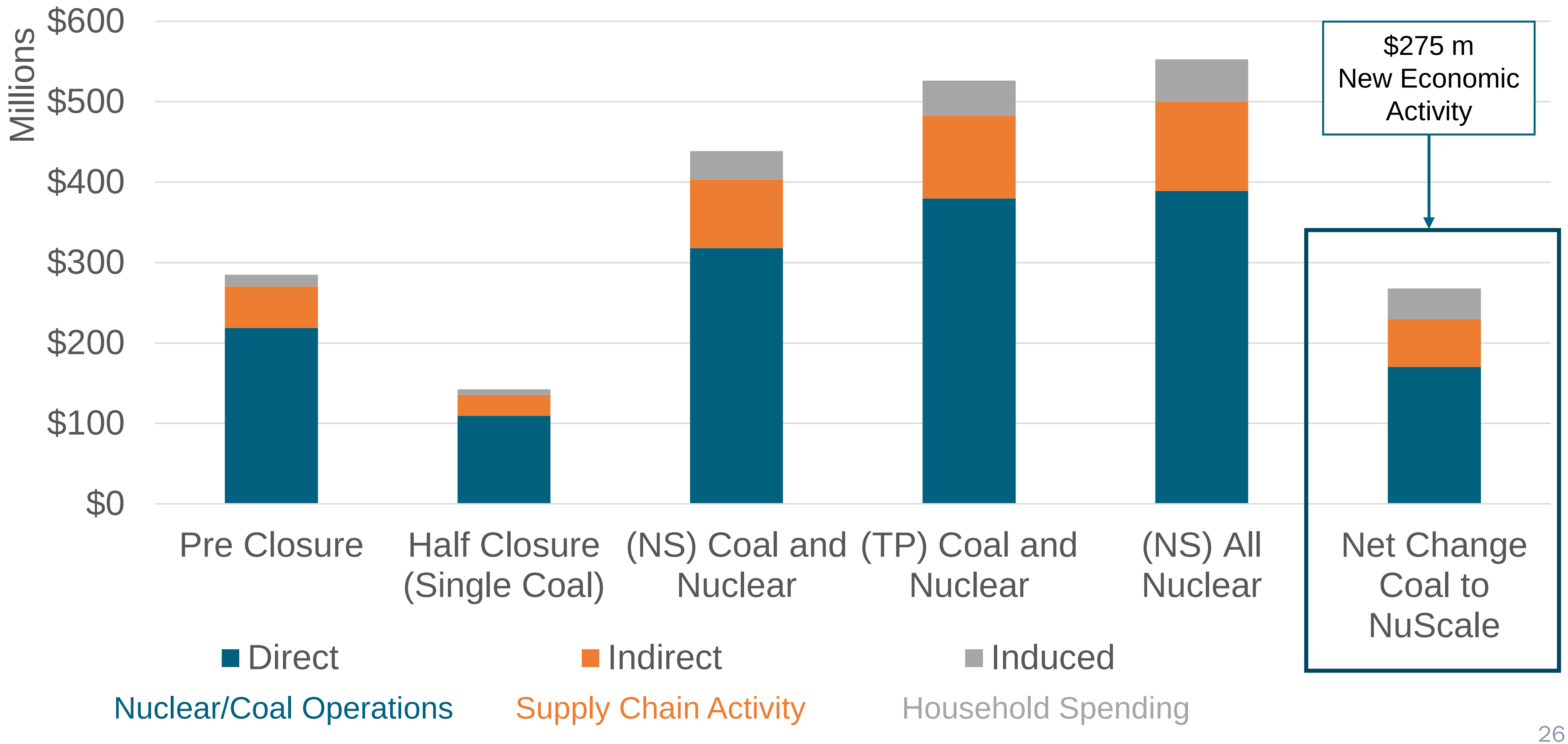
- Combined, composite analysis region
- Added nuclear sector using state production function
- Verified costs of employment
- Compared industry revenue forecasts with IMPLAN
- Estimated coal fired generating facility MW per employee
- Utilized publicly available reports on NuScale and TerraPower for employee counts and electricity production
- Leveraged tax records for facility tax impact figures

2-Approach: Impact Scenarios

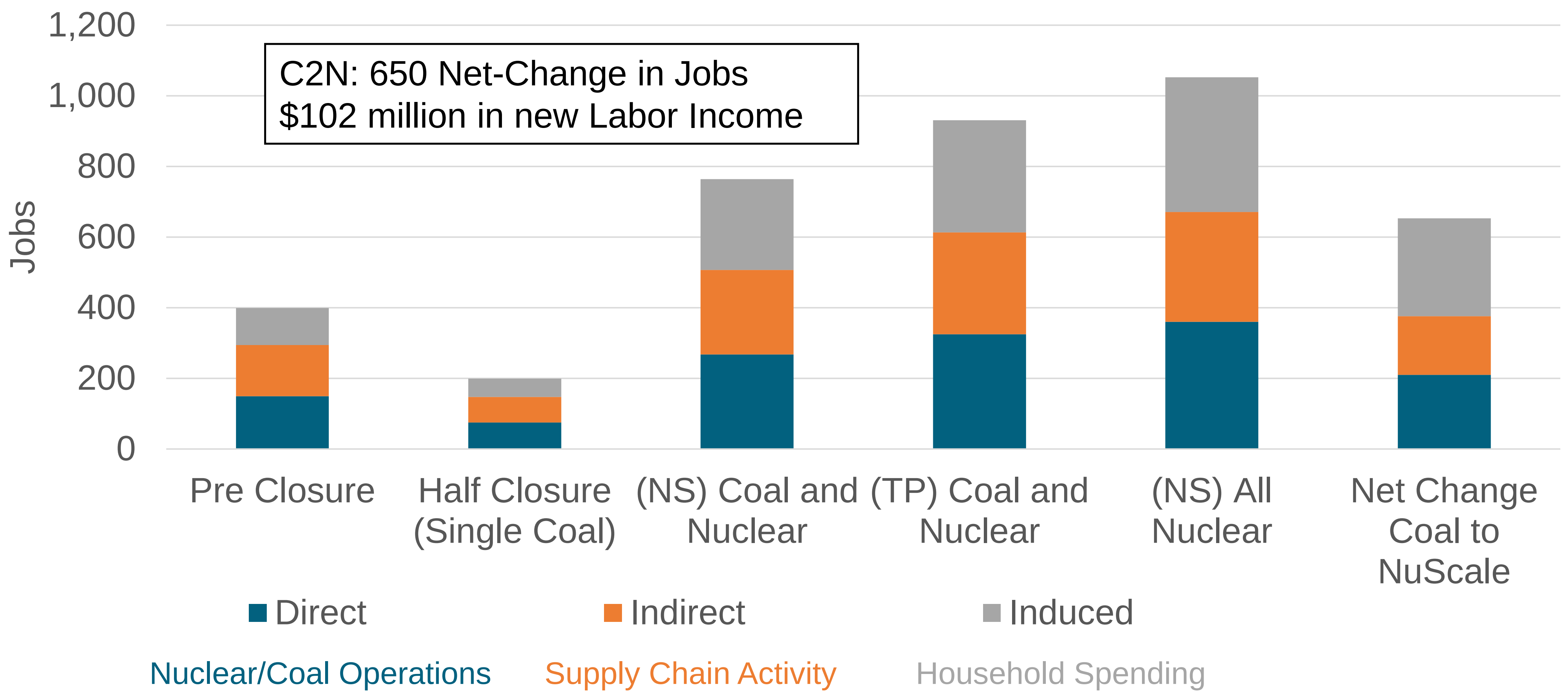
Pre-Closure	Half Closure	Coal and Nuclear	All Nuclear

• 150 Coal plant jobs
• 1,234 MW
	• Single generating Unit 2 Retired
	• 75 jobs
	• 600 MW
		• Single coal Unit 2 Retired
		  • 75 Jobs
		• Small Modular (NuScale or TerraPower) design
		  • 193-250 Jobs
		  • 345-462 MW
			• Dual unit coal Unit 2 Retired and Unit 1 Retirement
			• 12-Module NuScale reactor design
			• 360 Jobs
			• 924 MW

3-Results: Output Impact, value of industry production



3-Results: Employment Impact, jobs created or sustained



2-Approach: IMPLAN Environmental Impacts

- Based on EPA's Environmentally Extended Input-Output (EEIO) Model
- Business volume in $ by industry correlated with environmental impacts

Included

- Criteria Pollutants
- Greenhouse Gasses
- Land Use
- Nitrogen & Phosphorus Release to water
- Pesticides
- Toxic Chemical
- Water Use

Not Included

- Coal Mining
- Nuclear fuel production
- Long-term nuclear waste storage
- Legacy ash ponds
- Impacts outside the 4-county area

3-Results: IMPLAN Environmental Impact Estimates

Impact Type	Scenario (Jobs)	Criteria Pollutants (Kg/Year)	Greenhouse Gases (Kg/Year)	Land Use (Sq Meters)	Mineral Use (Kg/Year)	Nitrogen and Phosphorus Release to Water (Kg/Year)	Pesticide Emissions (Kg/Year)	Toxic Chemical Releases (Kg/Year)	Water Use (Cubic Meters)
Direct (PP Only)	**Pre-Closure (150)**	**5,406,176**	**2,595,982,880**	**1,833,454**	**0**	**36,656**	**0**	**28,790**	**297,446,454**
	Nuclear (150)	**4,006,213**	**7,977,364**	**1,358,670**	**0**	**27,167**	**0**	**21,335**	**220,420,840**
	Nuclear (270)	7,211.183	14,359,256	2,445,606	0	48,894	0	38,402	396,757,512
	Nuclear (360)	9,614,911	19,145,674	3,260,808	0	65,192	0	51,203	529,010,016
Total	Pre-Closure (150)	6,222,468	2,744,173,698	3,211,800	774,813	135,989	5	32,379	334,603,463
	Nuclear (150)	4,776,462	157,455,878	2,029,567	677,238	129,434	7	25,005	258,428,602
	Nuclear 270	8,597,632	285,220,581	3,653,221	1,219,028	232,981	13	45,009	465,171,484
	Nuclear (360)	11,463,509	380,294,108	4,870,961	1,625,370	310,641	17	60,012	620,228,645

Env. impacts decrease across all categories when employment is equalized

-99% from Pre-Closure (PP Only)

-86% from Pre-Closure (Total)

2-Approach: Workforce Transition Analysis

- **Assessed change from all-coal to all-nuclear scenario**
- **Approach 1 – Bureau of Labor Statistics Data**
  - Staffing pattern comparison by detailed occupation
  - Direct (power plant) jobs only
  - Used to verify accuracy of IMPLAN Data
- **Approach 2 – IMPLAN Data**
  - Includes direct, indirect, and induced jobs
  - Allows for transition from coal-to-supply chain or coal-to-community workforce transitions
  - Education Requirements

3-Results: Statewide Workforce Transition

- **Workforce Transition Scenario**
  - Loss of 150 CPP jobs, Addition of 360 NPP jobs
- **Total Impact on Workforce Transition (IMPLAN)**
  - 797 net jobs added (including jobs at plant, suppliers, and community)
  - Fractional job josses from transition
- **Transitions Between Same Occupations**
  - Electrical Engineers
    - Fossil Closure: -7 jobs
    - Nuclear Operations: +10 jobs
- **Transitions Between Similar Occupation**
  - (Fossil) Power Plant Operators: -25 Jobs
  - (Nuclear) Nuclear Power Reactor Operators: +45 jobs

4-Summary with Social and Environmental Justice Impact

- **C2N can result in up to about 650 new jobs to the region**
  - 210 NPP, 166 Supply Chain, 277 Community
- **Increased income levels**
  - Adding jobs with >$100,000/YR salary
  - Regional median income $56,000, median home value $119,000 and pre-COVID poverty rate was 10%
  - BD or Higher Education: County 19%, US Average 33%
- **C2N transition implies a local workforce transition for CPP workers**
- **C2N yields economic activity that generates tax revenue to support the tax base in economically disadvantaged community**
- **C2N transition reduces greenhouse emissions in the region**
  - 99% reduction when comparing CPP to NPP, 86% reduction for community impact
  - Increase in regional environmental indicators results from increased population moving to the region

Summary and Conclusions

Summary of Study Results

- The drive to a net-zero GHG emissions economy by 2050 has resulted in a reassessment of the needed energy mix with a focus on “clean firm” sources of energy that are available on demand. The main source of clean firm energy is nuclear and the ~95 GW of existing nuclear capacity in the United States currently produces roughly half of all U.S. emissions-free electricity.
- This study estimates a substantial amount of coal capacity in the U.S. is amendable to converting to nuclear power plants – over 250 GW.
- Results show that re-using coal infrastructure at nuclear power plants can save on nuclear construction costs – estimates range from 15% to 35%.
- The study estimates that repurposing coal power plants to nuclear power plants can make communities better off economically while at the same time improving environmental conditions – an especially important finding for disadvantaged communities.
    - Compared to coal plants, nuclear plants spend less on fuel but more on labor, so local economic activity increases, wages go up, and new, permanent jobs are added to the community. Modeling results show for a large plant conversion (1,200 MW), the impact is over 650 new jobs in the community, over $100 million more in wages, and up to $275 million more in annual total economic activity.
    - At the same time that economics improve for communities, so do environmental indicators. Again, comparing all coal to all nuclear, GHG emissions in the region fall by 86%.